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# Development of a ground operations demonstration unit for liquid hydrogen at Kennedy Space Center

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**Abstract**

NASA operations for handling cryogens in ground support equipment have not changed substantially in 50 years, despite major technology advances in the field of cryogenics. NASA loses approximately 50% of the hydrogen purchased because of a continuous heat leak into ground and flight vessels, transient chill down of warm cryogenic equipment, liquid bleeds, and vent losses. NASA Kennedy Space Center (KSC) needs to develop energy-efficient cryogenic ground systems to minimize propellant losses, simplify operations, and reduce cost associated with hydrogen usage. The GODU LH2 project will design, assemble, and test a prototype storage and distribution system for liquid hydrogen that represents an advanced end-to-end cryogenic propellant system for a ground launch complex. The project has multiple objectives and will culminate with an operational demonstration of the loading of a simulated flight tank with densified propellants. The system will be unique because it uses an integrated refrigeration and storage system (IRAS) to control the state of the fluid. The integrated refrigerator is the critical feature enabling the testing of the following three functions: zero-loss storage and transfer, propellant densification/conditioning, and on-site liquefaction. This paper will discuss the test objectives, the design of the system, and the current status of the installation.


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*Keywords:* Liquid hydrogen; cryogenic refrigeration; space launch systems.

## 1. Background

NASA operations for handling cryogens in ground support equipment have not changed substantially in 50 years, despite advances in the field of cryogenics. NASA typically loses 50% of the hydrogen purchased[1]. Since hydrogen production, liquefaction, storage and transfer is an energy intensive process, this represents a large quantity of energy lost. The Shuttle Program's cost for cryogenic propellants for Stennis Space Center and KSC was over $20M per year between 2006 and 2009. This number represents a mature program with minimal engine testing and a low annual flight rate. NASA needs to develop energy-efficient cryogenic ground systems to minimize propellant losses, minimize the size of new storage tanks, simplify test and launch operations, minimize helium consumption, and reduce the environmental impact of the space program. The GODU LH2 project was conceived to demonstrate advanced cryogenic operations that minimize capital and operations cost, including power, system size, lost consumables, and manpower. It is hoped that successful demonstration of these energy efficient cryogenic operations in a relevant scale and environment will enable their incorporation in future spaceport architectures. The system design is also relevant to a number of low temperature energy systems, and potential collaborations will be addressed.

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### 1.1. Integrated refrigeration and storage

Although NASA was one of the drivers of the development of large scale LH2 systems, commercial industry has since passed us by. The state of the art in cryogenic systems has advanced greatly in the past 50 years, especially in the field of cryogenic refrigeration. Hydrogen temperature refrigerators are available for a wide range of capacities and these refrigerators are critical to achieve active thermal control of the cryogens. Depending on the refrigerator capacity, this system can be used for zero boil off storage, in situ liquefaction, or propellant conditioning/densification. This Integrated Refrigeration and Storage (IRAS) concept allows liquid hydrogen to be stored in a quasi-equilibrium state. The simplest example of this is a zero boil off system (ZBO). The IRAS concept is novel in that it cools the liquid directly at the storage site and is designed to operate with refrigerator capacity to system heat leak ratio ($R = Q_R/Q_{HL}$) greater than 1. Continuous operation of the cryogenic refrigerator minimizes the overall refrigeration capacity required and increases reliability compared to systems designed to operate intermittently. Cooling the liquid directly allows for control of the bulk temperature of the fluid as opposed to pressure control of the ullage using vent and relief valves. This also enables easier depressurization of tank ullage pressure and bulk fluid conditioning for greater vehicle loading control. Conditioning operations can also serve as a store of refrigeration energy for load balancing. Higher $Q_R/Q_{HL}$ratios allow for advanced operations such as propellant densification and liquefaction, and future spaceport and test center architectural visions culminate with a distributed production capability to individual pads for liquefaction and zero loss storage and transfer. For these systems, launch customers will only be billed for hydrogen after it crosses the flight to ground umbilical, not what gets purchased hundreds of miles away many months before launch.

### 1.2. Future applications

The new Space Launch System being designed for launch at KSC complex 39B is trying to plan its hydrogen procurement strategy for future operations. Typical space launch requirements are unique in the industrial gas supply industry. The usage state is still liquid to fit an engine start box while most users just need the gas. And launch operations are intermittent as opposed to daily supply. The early SLS flights are four years apart and later flight rates are every two years and estimated quantities are over 1million gallons per launch. And scrub turnaround operations increase the initial quantity required by 30%. This storage challenge required greater operational efficiency than in the past and using refrigeration to mitigate boil off is important. Once these systems are proven in SLS, they can be incorporated elsewhere at KSC and Cape Canaveral. If the space coast area gets a hydrogen production plant, these refrigerators can also be used to liquefy the gas. By integrating the needs of the SLS, future commercial launch operators, and the defense departments launch programs a true spaceport architecture can be achieved where the hydrogen supply is treated as a common utility between customers. This will help reduce launch costs and streamline operations.

## 2. Project goals and test objectives

The ability to actively control the thermodynamic state of the liquid hydrogen for spaceport applications is a new concept, and there will be a learning curve associated with implementation. Currently the concept has been proven at the 180 liter scale using a Gifford McMahon cryocooler in a partnership with the Florida Solar Energy Center [2]. Storage and handling characteristics have been evaluated as the hydrogen volume increased from empty to 90% full via in situ liquefaction. Pressurization and depressurization cycles at various liquid levels were performed, and data was collected on thermal stratification. The system behaviour is now understood and testing at a more relevant scale in an operational environment is the next step. The GODU LH2 project will design, assemble, and test a prototype storage and distribution system for liquid hydrogen that represents a complete end-to-end cryogenic propellant system for a ground launch complex. The project has multiple related objectives and will culminate with an advanced operational demonstration of the loading of a simulated flight tank with densified propellants. The system will be unique because it uses an integrated refrigeration and storage system (IRAS) to remove heat leak and thermal energy from the fluid. The integrated refrigerator is the critical feature enabling the control of the propellant state.

The overall goal of the project is to demonstrate efficient LH2 operations on a relevant scale that can be projected onto future Spaceport architectures. This goal will be demonstrated by completing primary test objectives in the area of efficient and reliable integrated liquid hydrogen systems. There are three primary test objectives for GODU LH2. These are:

I. Demonstrate zero loss storage and transfer of LH2;
II. Demonstrate hydrogen densification in storage tank and loading of a flight tank;
III. Demonstrate hydrogen liquefaction using close cycle helium refrigeration.

### 2.1 Zero loss storage and transfer

Past studies detailed loss mechanisms in historical shuttle data[2]. Replenishment inefficiency, from the tanker at the point of purchase to delivery in the launch site storage tank, accounted for 26% of the losses. Normal evaporation (boil-off) in the storage tank between launches/tests was another 24%. Ground losses (chill down) during propellant loading or scrub operations accounted for 15%. And flight tank losses during propellant loading or scrub operations were the largest contributor with 35%.

The system is designed with refrigeration capacity will be sized to allow for zero boil-off storage in the tank, re-liquefaction of vapours normally lost in the chill down of transfer lines, re-liquefaction (instead of venting) of ullage gas used for pressurization, and all losses from tanker operations. This system will attempt to demonstrate techniques to recover 65% of the hydrogen lost today.

*2.2 Propellant densification/conditioning.*

Densified propellants that are sub-cooled below their normal boiling point enable minimized vehicle size, increased payload mass fraction, and extended loiter time before the onset of venting of in-space storage. Densified propellants have been identified as a promising option for increasing the performance of chemical propulsion systems and were considered for the Space Transportation System (STS), X-33, National Aerospace Plane (NASP), and the Second Generation Reusable Launch Vehicle (RLV) programs. Excessive complexity of the associated ground systems and limited ground operations experience were factors that hampered the adoption of densified propellants in earlier programs. The integrated refrigeration and storage approach has been identified by laboratory-scale testing to be a simple, reliable, and efficient method of producing densified propellants. This has applications in other LH2 transport systems as an energy storage medium. Thermal control and pressure control issues associated with the flight tank loading process must still be resolved in addition to building an operational experience base using a full-scale system. With integrated refrigerators, advanced insulation, and novel pressurization schemes, densified hydrogen will be loaded into a simulated flight tank, thermal stratification will be measured and controlled, and a target bulk propellant temperature of 16.5 K in the flight tank will be demonstrated.

*2.3 Liquefaction*

The optimal solution to reduce hydrogen losses at the launch site may involve local production and liquefaction. Industrial gas companies are organized to meet the needs of other customers, and the unique needs of the space industry are not being met efficiently with the current infrastructure. Small-scale liquefaction operations (50 gallons per day) will be demonstrated in the GO DU LH2, and the system can be modified to increase performance as needed. Using a central hydrogen production plant with pressurized GH2 pipelines to individual pads would allow on mass input to a liquefier and the refrigerator liquefies 100% of the incoming stream. With a hydrogen turbo-alternator in line, the compression energy at the production plant can be partially recovered by the expansion process.

## 3. System design

The GODU LH2 system consists of these major subsystems: storage tank, refrigeration system, simulated flight tank, transfer and vent systems, pneumatics, command and control/instrumentation, and facility site and safety preparations. A functional diagram of the system is shown below in Fig. 1. These are described in more detail below.

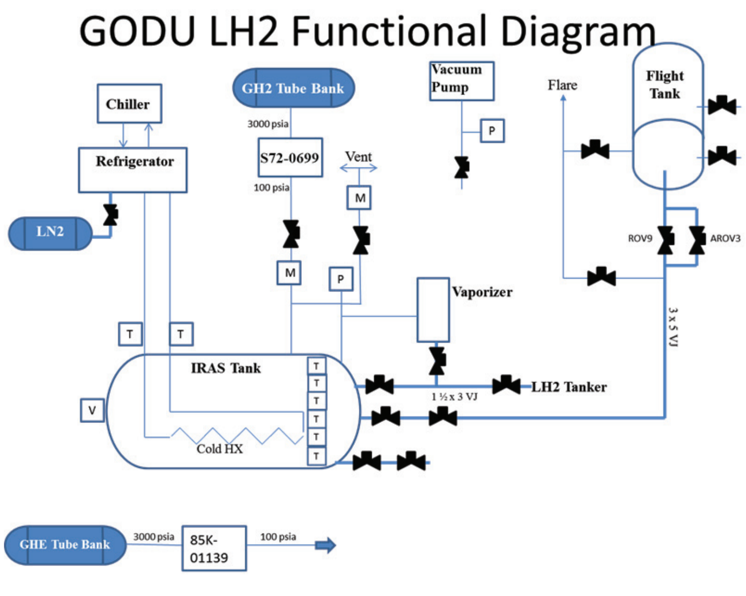


Fig. 1. GODU LH2 functional diagram.

*3.1. Integrated refrigeration and storage tank*

The IRAS tank is a 125 $m^3$ vacuum jacketed vessel with multi-layer insulation, three liquid ports, one vent port, one cold gas supply port and several smaller sense lines. The liquid ports are used for filing and vaporizer supply, liquid supply to the flight tank, and a spare for future test possibilities. The vent port accommodates pressure relief valves, manual and remote vent valves, and pressurization legs from the pneumatic and vaporizer systems. The IRAS tank has a manway on the top with a bayonet plug that has been modified to allow for refrigerant line penetrations for GHe flow into and out of the inner tank to the submerged heat exchanger coil. The HX coil was designed to promote maximum refrigeration heat transfer and distributed cooling in the tank. The manway also has a cold gas supply port for GH2 inlet from the liquefaction leg and the HETL return leg. The inner tank will also be modified to allow for temperature sensing in the liquid region. Structural modifications were needed to allow the tank to withstand sub-atmospheric operations. Nine internal rings were added to provide stiffness in the event of an inner tank vacuum and a loss of vacuum in the annulus.

*3.2. Refrigeration*

The cryogenic refrigerator is the critical component needed for this system. An 850 W at 20K Brayton cycle refrigerator, manufactured by Linde, has been procured for this project. The refrigeration system will be located inside a standard ISO shipping container for portability and the entire container will be purged with outside air to prevent the system from being exposed to hydrogen gas. The refrigerator provides cooling to the inside of the IRAS tank by means of a cold gas circulation system. The cold helium absorbs heat leak from the stored liquid hydrogen via a submerged heat exchanger. Additional heat is absorbed in the transport lines and thru the active components. This heat is then rejected by the cryocooler to a chilled water circulation loop. There will be a single reverse Brayton cycle refrigerator that is capable of providing roughly 22 g/s of helium at 13.6 K to the IRAS tank with a single VJ supply and return line. The refrigerator can deliver 350W of cooling at 20.3 K without LN2 pre-cooling, and 800W at 20.3 K for maximum capacity using LN2 pre-cooling.

*3.2. Simulated flight tank*

The simulated flight tank is planned to be a Centaur III structural test article. The Centaur tank is a common bulkhead LOX and LH2 tank and has external foam insulation. It is undetermined whether the LOX or LH2 tank will be the one used for the demonstration. In either case, there will be strict pressure and delta pressure restrictions across the common bulk head during the use of the tank. These restrictions and the tank interfaces are undefined at this point. No liquid oxygen (LOX) will be used during any of these tests.

*3.4. Transfer and vent system*

The gaseous and liquid transfer subsystem includes all lines, valves, and supports required to flow liquid hydrogen from the tanker supply to the main storage tank, from the storage tank to the simulated flight tank, and the gaseous hydrogen from these systems to the vent and flare systems.

*3.5. Pneumatics*

To reduce project cost, several pneumatic panels and gas storage bottles will be reused from the shuttle program to provide gaseous helium, hydrogen and nitrogen to the system. Two 16.5 mPa psi movable storage units (MSU) provide a 2265 $m^3$ helium storage capability, and three additional 16.5 mPa MSU's store up to 3400 $m^3$ of gaseous nitrogen. Gaseous hydrogen will be supplied to the site by compressed gas trailers. The facility nitrogen panel reduces the 16.5 mPa down to several 5 mPa sources as well as up to twenty 700 kPa sources used for valve actuation, panel inerting, and purging of lines. Gaseous hydrogen is regulated from 25.5 mPa down to 1030 kPa and will be used for liquefaction supply as well as purge and pressurization of lines and tanks.

*3.6. Command and control/instrumentation*

The command and control and data and acquisition system will use commercial Allen Bradley PLC and interface modules. Numerous control loops will be programmed to control refrigeration capacity, liquefaction rates, transfer and replenish flow rates, and system pressures. This subsystem also includes the necessary hazardous gas and fire detection systems as well as video cameras. Advanced instrumentation, including real time composition measurements, will be developed and tested in the system operation. The C&C system for the initial testing will not use any advanced features such as autonomous control or fault detection, isolation, and recovery.

The control system will operate the refrigerator in two different modes which are defined as zero boil-off (ZBO) mode and the densification mode. Zero boil-off mode regulates the internal refrigerator trim heater to adjust total capacity based on a control signal that reads either the IRAS tank pressure or bulk fluid temperature. When the IRAS tank pressure/temperature is above the set pressure, the refrigerator increases output causing the tank pressure/temperature to decrease. When the IRAS tank pressure/temperature is below the set pressure, the refrigerator output decreases and ambient heat leak causes the tank pressure/temperature to increase. Due to the unknown tank heat load, it is not known if the LN2 pre-cooling system will need to be operated while the refrigeration system is in ZBO mode.

The cryocooler will operate at full power mode during propellant densification and liquefaction test operations. The control signal to the refrigerator always requires the refrigerator to operate at 100% capacity with LN2 precooling. During densification operations, the IRAS tank pressure will decrease until it reaches a system equilibrium temperature where the cryocooler refrigeration power will equal the heat load on the tank and refrigeration system. The estimated minimum temperatures for the system are 16.5 K.

During liquefaction operations, the refrigerator operates at full power, but the tank pressure will be controlled by regulating the gaseous hydrogen inlet flow rate using the liquefaction mass flow controller (MFC). The incoming hydrogen gas flow stream will also be pre-cooled in a liquid nitrogen heat exchange in addition to flowing through an ortho hydrogen to para hydrogen conversion catalyst bed.

### *3.7. Site and safety*

The M7-0912 facility, and the adjacent field to the east, have been approved by the Facility Management Board as the GODU LH2 test site. Facility modifications were performed to provide necessary power to the field. A 500 kVA transformer is used to step down the 13.2 kV power supply to 480V required by the refrigerator and chiller. A secondary 75 kVA transformer reduces the 480 V power to 120/208 V for command and control and instrumentation purposes. The control room is a trailer located 500 feet away from the tank inside a 100'x100' metal clamshell building. The clamshell also serves as the staging area for equipment, and has a small machine shop for working on fabrication of tubing, conduit, and structural systems.

## 4. FY 15 testing plan

Testing of the system behavior with liquid hydrogen will start in October 2014. At the beginning of the test campaign, the IRAS tank will be partially full of liquid nitrogen after the IRAS tank validation tests. The refrigerator will have undergone similar verification tests in a bypass mode and all transfer lines will be cold shocked and leak tested. All pneumatic and C&C functions will have been verified. The remaining liquid nitrogen in the tank will be drained, and the tank will undergo a series of purge/vacuum cycles with GH2 to remove gaseous contaminants from the vessel. This will be done as quickly as possible in order to preserve the cold tank temperatures as much as possible. The tank will have a residual pressure of pure gaseous hydrogen remaining when the refrigeration system will be powered up. Gaseous hydrogen will continue to flow into the tank to maintain positive pressure as the refrigerator slowly chills down the tank walls to 20 K and liquefies hydrogen in the bottom of the tank. This chill down/liquefaction process will continue for weeks until there is a minimum of 3 $m^3$ of LH2 in the tank. At this point the system will be ready for liquid hydrogen to be supplied via tankers.

A zero loss tanker offload process will be attempted each time a tanker is delivered. The tanker will arrive with a slightly higher pressure and temperature due to heat leak during the transportation process.

After each tanker offload, with liquid levels in the tank of 30, 60, and 90%, a series of tests will be performed. After steady state conditions have been achieved, a week long zero boil off test will be done. The refrigerator will be used, hopefully without LN2 precooling, to maintain LH2 in saturated state between 1.7 and 5.2 kPa using the refrigerator. Tank temperature profiles as well as tank pressures will be monitored. Next, a boil off test will be done to characterize the tank thermal performance without refrigeration. We will power down the refrigerator and chiller and open the tank vent valve. The tank will self-pressurize and vent through the boil off mass flow meter to quantify the tank evaporation rate over a period of one week. Again the tank temperatures will be monitored and recorded to measure temperature gradients.

After the performance test, gaseous hydrogen will be introduced into the tank for liquefaction. We will power up the refrigerator and chiller in full power mode and turn on LN2 precooling. Operators will pressurize GH2 panel to 517 kPa and open liquefaction mass flow controller isolation valve. The mass flow controller will be set to 6.9 kPa set point pressure, and we will find the steady-state liquefaction rate over 5 days using LN2 precooling and ortho-para conversion of the inlet stream. The gas inlet port will vary between the ullage region and the liquid region to measure the effect of different liquefaction locations. Next, densification testing will occur. The liquefaction gas supply and mass flow controller will be turned off. We will leave refrigerator on full power mode until steady state conditions are achieved in the tank and then maintain steady operation for two days. Tank temperatures and pressure will be monitored. This will reduce the tank pressure to as low as 13.7 kPa, so helium purges on IRAS valve stems and flanges will be activated to prevent atmospheric intrusion. Finally pressure control testing will occur where the GH2 panel will be activated. While the tank is in sub-atmospheric state, GH2will flow into tank ullage at high flow rates to attempt positive pressure control of the liquid. Operators will attempt to pressurize the tank to 137 kPa with both the refrigerator running and without.

Once pressurization tests are complete, the GH2 supply will be stopped and the refrigerator will be placed back into zero boil off mode. Once steady state is again achieved, another tanker will be connected and the tank will be filled to 60%. The set of tests above will be repeated for both the 60 and 90% fill level. It is expected that these tests will take 12 months to complete and IRAS tank testing will be finished by the end of September 2015. At that point, the simulated flight tank will be installed and a number of transfer and loading demonstrations will be performed.

## 5. Current status

As of July 1, 2014, the design of the system is complete, all major procurements have been executed, and the system is in final assembly. The chiller is installed and connected to facility power and will be serviced with water/glycol in July. The refrigeration system has been installed into the ISO container, and the high and low pressure helium connections between the compressor and refrigerator have been installed. The nitrogen and helium vent line has been installed, and the LN2 supply line is ready for installation. There are several helium tubes that still need to be connected and then the system will be serviced with high purity gaseous helium in July. The 480V power system is currently being connected and refrigeration system verification testing is planned for the beginning of August.

The IRAS tank modifications have been completed. The stiffening rings are installed and passed inspection by the PVS code shop inspector. The temperature rakes have been assembled and installed in the tank and the electrical connections have been routed to the manway. The heat exchanger assembly is complete, and the flex hose connections installed. The final manway connections and installation are set for early July.

All cryogenic VJ transfer lines and system vent/relief lines have been fabricated and assembled in the field. The VJ lines have been pressure tested and cold shocked in the shop and vacuum decay tests have been performed. The vent pipe has been cold shocked, pressure tested and leak tested and the components have been functionally verified. Relief valves were calibrated and installed alongside the burst disks.

All pneumatic panels and the helium and nitrogen storage units have been installed. Tubing connections between the storage and distribution panels are installed. Tubing downstream of panels to their usage locations are being installed and should be complete by the end of July.

Command and control panels are being fabricated in the shops and the C&C software is being written. Instrumentation modules are being written and data acquisition hardware and software is nearly complete. Hazardous gas detection units are being installed in the field along with hydrogen leak and fire detection.

## 5. Conclusion

NASA Kennedy Space Center cryogenic engineers are working on the installation and testing of prototype cryogenic system intended to demonstrate advanced liquid hydrogen handling operations. The central feature of the system is a cryogenic refrigerator that is integrated into a LH2 storage tank. This will enable operational testing of zero loss storage and transfer, densification, and liquefaction of the hydrogen. The system has been designed, major components have been fabricated, and final assembly is taking place in the summer of 2014. Testing with hydrogen is scheduled to begin in October 2014.

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